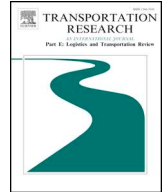


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# Transportation Research Part E

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## Handling financial risks in crude oil imports: Taking into account crude oil prices as well as country and transportation risks



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### ABSTRACT

Financial risks related to crude oil imports are certainly affected by crude oil price uncertainty. Our question is: How important is it to take also physical risks, such as the crude oil exporters' political risks and transportation risks into account when controlling financial risks in line with the importer's risk attitude when planning crude oil imports and transportation at a tactical level? In this paper, two-stage stochastic programming models are proposed to illustrate the problem, and a numerical test is conducted to better understand the effects of physical risks. The mechanism for controlling risk will be forward physical contracts. The results show that the real financial risk is much higher than the importer might believe if physical risks are not considered. Unless the importer is risk neutral, more forward crude oil will be imported when physical risks are considered, and the distribution of forward crude oil will depend strongly on correlations among risks.

### 1. Introduction

Crude oil is of strategic importance in all countries, and it is often crucial for a crude oil importer's national economy. Every import country wants to secure an uninterrupted availability of crude oil at an affordable price. But many crude oil exporters, particularly those located in the Middle East, Africa and Latin America, suffer political instability or have a high risk potential (Vivoda, 2009). The unstable political situations in these regions will create supply disruption risks for importers. There are also correlations between political risks of different exporters in the same region, since they are impacted by some common risk factors (Li et al., 2009). For example, the war in Yemen, with Iran and Saudi Arabia involved, leads to instability in the Middle East. Disruptions in supply will lead to an imbalance between supply and demand in the international crude oil market, and global crude oil prices will fluctuate. Since the global crude oil market is highly integrated, the crude oil prices of other exporters will also be affected. In addition to the political risks and crude oil price fluctuations of exporters, there are also transportation risks. Most crude oil is transported by ship. But the straits and canals in the maritime transportation network are exposed to risks due to political instability in neighboring countries, as well as terrorism, piracy, conflicts and other extreme events (Emmerson and Stevens, 2012). For example, the political instability in the Middle East threatens the safety of the Bab el Mandeb and the Suez Canal. If certain straits or canals are closed, the crude oil transportation will be affected.

Due to the political risks of exporters, transportation risks of straits and canals, and oil price uncertainty, crude oil import and transportation decisions are very challenging for importers, who want to control financial risks. But this problem is underexplored. In previous studies, the focus has mostly been on crude oil price fluctuations, and different hedging strategies are proposed. Chen et al.

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(2015) employed geometric Brownian motion processes to model oil price fluctuations, and determined the optimal oil procurement. Operational and financial hedging strategies are proposed by Ji et al. (2015) to manage risks caused by oil price fluctuation. Chang et al. (2011) used a dynamic multivariate GARCH to obtain a crude oil hedging strategy. Sukcharoen and Leatham (2017) proposed the use of vine copulas to capture characteristics of price changes and estimate multiproduct hedge ratios for a refinery to manage risks. In these studies, there are no considerations of selection of exporters, so the political risks of exporters are not taken into account. In addition, the transportation risks are also not considered.

In some studies, associated with crude oil import and transportation, risks of exporters or oil spill risks are taken into consideration (Li et al. 2014; Iakovou, 2001). But the risks are represented by parameters, without considering their stochastic nature. Therefore, in previous studies, physical risks have not been investigated to control financial risks. This is the gap in the literature that we address. Consequently, we study to what extent the physical risks should be taken into account when controlling financial risks at a tactical level for a potentially risk-averse importer. To achieve this goal, three two-stage stochastic programming models are proposed.

This paper contributes to the existing literature in two ways. Firstly, it is a first attempt to investigate and analyze tactical decisions related to crude oil import and transportation planning in the light of physical risks: Are they important or not? This way we complement previous studies that only consider oil price uncertainty. Secondly, this paper uses a quasi-real case to conduct numerical tests, and the qualitative aspects of the results provide managerial insights. For example, if only oil price uncertainty is considered, the actual financial risk will be substantially larger than it appears to be, as there are severe cost consequences in some scenarios. In addition, if physical risks are considered, more forward crude oil will be bought in the forward market to secure against the very same risks. Finally, the geographical distribution of forward oil purchases will be strongly affected by the correlations among risks when physical risks are taken into account. Hence, forward purchases are guided by more than oil prices and transportation costs. These managerial insights can help a crude oil importer better understand the role of physical risks and hence, make better decisions.

This paper is organized as follows. Section 2 reviews the relevant literature. Section 3 describes the problem, while Section 4 presents the mathematical formulation of the model. In Section 5, a numerical test is used for managerial insights. Finally, conclusions are discussed in Section 6.

## 2. Literature review

Our work is related to two streams of literature. The first stream focuses on hedging strategies for controlling financial risks of crude oil procurement, and the second stream is concerned with physical risks of oil exporters and oil transportation.

Because of supply, demand, price and other uncertainties, risk analysis and management has attracted much attention in the fields of logistics and operations management (Gavriilidis et al., 2018; Balliauw et al., 2019; Canbolat and Rothblum, 2019; Wang and Yao, 2019; Wang et al., 2019; Wen et al., 2019; Liu and Wang, 2019; Almasi et al., 2019). In terms of oil procurement, due to the great volatility of crude oil prices, a crude oil importer faces large financial risks. Based on the study of correlations between spot and futures prices (Silvapulle and Moosa, 1999; Alizadeh and Nomikos, 2004), different crude oil hedging strategies are proposed to manage these risks. The traditional hedging strategy is based on the minimization of the variance of the import portfolio, and the obtained minimum-variance hedge ratio is assumed to be time invariant (Ederington, 1979; Johnson, 1960; Myers and Thompson, 1989; Chen et al., 2003). Since the variance and covariance of the crude oil spot and the futures prices are time-varying, various GARCH class models have been developed subsequently, and the time-varying hedge ratio is optimized (Haigh and Holt, 2002; Jalali-Naini and Kazemi-Manesh, 2006; Ghorbel and Trabelsi, 2012; Chang et al., 2011). Recently, new methods like the vine copula and polynomial projection models are proposed to calculate the optimal hedging ratio (Sukcharoen and Leatham, 2017; Chen et al., 2012).

In addition to financial hedging, some researches also consider operational hedging strategies to control financial risks. Ji et al. (2015) proposed an integrated hedging strategy through operational hedging, together with financial hedging, to control the financial risks of crude oil procurement due to oil price fluctuations. The inventory and the nonlinear CDU Fractionation Index (FI) model are used for the operational hedging, and crude oil futures and call/put options are used for financial hedging. In order to minimize the CVaR associated with the total costs, the quantity of crude oil procured from the spot market and the quantities on each contract in each time period are determined. In order to control the financial risk, Park et al. (2010) investigated how spot, futures and option contracts, as well as the operational plan, influence oil procurement decisions based on two-stage stochastic programming and the price scenarios. Since there are different methods for calculating the hedging ratio, the hedging performance evaluation also attracts attentions in the literature (Yun and Kim, 2010; Toyoshima et al., 2013; Cotter and Hanly, 2012).

In the second stream, Sun et al. (2014) evaluate the total oil import risks of China, including exporter's country risk and transportation risk. The data of the International Country Risk Guide (ICRG) are used to represent the country risk of oil exporters. Li et al. (2014) take country risks of exporters into consideration in order to optimize crude oil imports. In terms of transportation, the transportation costs are the main focus (Hennig et al., 2012, 2015; de Assis and Camponogara, 2016; Aizemberg et al., 2014; Kazemi and Szmerekovsky, 2015). Since oil spills in narrow shipping waterways can also lead to a blockade, which can incur high costs to the world economy (Qu and Meng, 2012), and also in order to protect the marine environment (Jin and Kite-Powell, 1999), oil spill risks are considered when optimizing maritime transportation routes of crude oil. Iakovou (2001), Siddiqui and Verma (2013, 2015) presented a model with oil spill risk and transportation cost objectives to derive maritime transportation routes for crude oil tankers.

However, it is not sufficient to only consider oil spill risks since straits and canals are exposed also to transportation risks from extreme events (e.g., conflicts and piracy). Furthermore, the above exporters' risks and oil spill risks are set as parameters, they are not properly captured to control the financial risks they cause. Based on the above literature review, we can conclude that previous

studies, such as the studies of Ghorbel and Trabelsi (2012), Chen et al. (2012), Ji et al. (2015), Park et al. (2010), only considered oil price fluctuations to manage risks in the oil procurement process. However, there are also other factors, such as the availability of crude oil and transportation which may need to be taken into account for financial risk handling, but there is a lack of such studies. Therefore, differently from the existing literature, this paper aims to investigate, in addition to the oil price uncertainty, whether it is necessary to take the physical risks into account when planning crude oil import and transportation, so as to control the overall financial risks. This paper can therefore be regarded as a supplement to the existing literature. And the risk-averse attitude of the importer is modeled by the conditional value at risk approach (Fernández et al., 2019; Li et al. 2018).

### 3. Problem description

To reduce the importers' exposure to crude oil price fluctuations and physical risks, and thereby controlling the overall financial risks, we use crude oil hedging in this paper. The hedging instruments considered are forward physical contracts. In a forward physical contract, the importer and the exporter will reach an agreement about a certain volume of crude oil and a fixed price as well as a prescribed delivery date. However, if the exporters are involved in a conflict at the prescribed delivery date, they are possibly not able to deliver the total volume of crude oil agreed in the contracts. According to the degree of involvement in a conflict, they may be able to deliver a certain percentage of the agreed volume, such as 40% or 70%. The importer may still purchase crude oil from the spot market if the hedged volume is not sufficient, but not from exporters that are in conflicts. This paper introduces the *delivery ratio* of the forward physical contract to represent the political risks of exporters.

It is difficult to model transportation risks. If there are events in certain straits or canals, the transportation capacity of the straits or canals will be reduced. This paper uses the planned volume of transported crude oil through straits and canals as the base for calculating reductions, that is, if there are conflicts affecting straits and canals, only a proportion of the planned volume of crude oil transported through those straits or canals can be accomplished. While it is fairly easy to understand what a 20% reduction means in total volume, it is not easy to distribute this among the different importers. We do it by reducing the planned volume for each importer by that given percentage. The *transportation ratio* of the planned volume is introduced to represent the transportation risk of straits and canals. Hence, as we shall indeed do, we need to determine the planned amount.

Let  $G = (N, A)$  denote the maritime transportation network for imported crude oil, where  $N$  is the set of nodes and  $A$  is the set of arcs. Fig. 1 shows an example. In the figure, the set of exporters is denoted by  $N_1$ , and this paper only considers one importer denoted by  $N_2$ , and the set of other nodes in the network is denoted by  $N_3$ , where  $N = N_1 \cup N_2 \cup N_3$ . The arc set comprises the set of straits and canals denoted by  $A_1$ , and the set of other transportation arcs denoted by  $A_2$ , where  $A = A_1 \cup A_2$ . Only arcs  $(i, j) \in A_1$  have transportation ratios to represent their transportation risks, while arcs  $(i, j) \in A_2$  do not have transportation risks. The crude oil purchased from forward physical contracts and the spot market will be transported through this network from exporters to the importer. When some straits and canals are affected by extreme events and can only transport a proportion of the planned volume, the remaining planned volume will be transported by other straits and canals, if at all possible. For example, if arc (11, 12) can only transport 80% of its planned volume, the remaining 20% can be transported through arc (11, 13) or (11, 14). This paper assumes that for straits and canals that are not affected by extreme events, their capacities are unbounded. Our problem is to investigate, in addition to the crude oil price uncertainty, whether the physical risks should be considered when deciding, at a tactical level, the volume of forward physical contracts from each exporter and the planned volume transported through each arc to control financial risks.

### 4. Model

#### 4.1. Model development

In this paper, two-stage stochastic programming models are proposed. The stochastic factors we want to handle are spot prices for crude oil, as well as the physical risks. Marginal distributions, as well as the correlations between the different random phenomena are taken into account, resulting in a set of scenarios. The first-stage decisions include the agreed volumes of crude oil in the forward

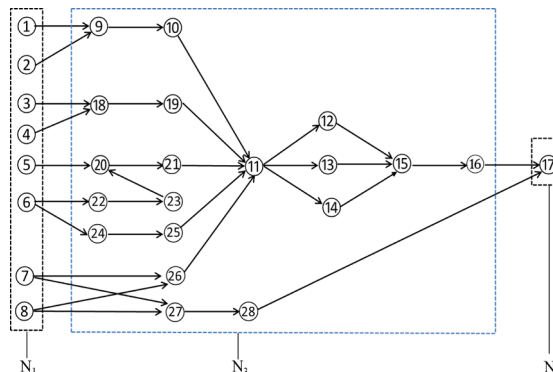


Fig. 1. An example of a maritime transportation network for importing crude oil.

physical contracts signed with each exporter, and the planned volume of crude oil transported on arc  $ij$ . In the second stage, where the stochastic factors are realized, decisions regarding the volume of crude oil imported from each exporter in the spot market, and the actual volume of crude oil transported on arc  $ij$  will be made based on the realized scenarios and the first-stage decisions. The objective of the model is to minimize the expected total costs of importing and transporting crude oil. But due to the uncertainties, and the large amount of money required for importing crude oil, the importer needs to control its financial risks. Risk is handled by conditional value-at-risk (CVaR) constraints on the total costs, restricting the expected total costs in the worst case scenarios to be under the predetermined maximal CVaR values. For example, given a confidence level of 95% and a CVaR value of \$1,000,000, the CVaR constraints would restrict the expected total costs in the worst 5% scenarios to be under \$1,000,000.

In order to know whether the physical risks should be taken into account to control the financial risks by forward physical contracts, three two-stage stochastic programming models are proposed. In Model 1, only spot prices are considered uncertain, and the physical risks are not taken into account. However, in reality, these risks exist even if they were not considered while planning, so we want to see how the decisions obtained in Model 1 actually behave. Therefore, in Model 2, the first-stage decisions of crude oil contracts in the forward market and the planned volume of crude oil transported on each arc, obtained from Model 1, are set as input. When the physical risks are realized in the second stage, the forward crude oil possibly cannot be fully delivered or the forward crude oil cannot be transported, so crude oil import decisions in the spot market and actual transportation decisions need to be adjusted to meet the demand, and the real expected total cost of using Model 1 can be evaluated by Model 2. So Model 2 is actually an evaluation model for Model 1. In Model 3, not only spot price uncertainty, but also the physical risks are considered. This paper will use the three models in the numerical test to understand the importance of the physical risks when tactically planning crude oil imports.

Before the models are formulated, the following assumptions are made. First, we only consider maritime transportation of crude oil. Second, the transportation cost of each arc is proportional to its length. Third, the planning period is three months. Some crude oil will arrive during the planning period, some will be on the way and arrive during the next period. It is rolling and never ends. But this paper looks at a single three months period, which captures the main structure of the tactical forward crude oil and transportation planning, and delivery.

#### 4.2. Mathematical formulation

The notations used in Model 1 are as follows:

Sets

$N_1$	Set of exporters
$N_2$	The importer
$N_3$	Set of other nodes
$N$	Set of all nodes in the maritime transportation network for imported crude oil, $N = N_1 \cup N_2 \cup N_3$
$A$	Set of all arcs in the maritime transportation network for imported crude oil
$S_1$	Set of scenarios for crude oil spot price

Parameters

$P_{1i}^F$	Price per ton of crude oil agreed in the forward physical contract signed with exporter $i$
$P_{1is}^S$	Price per ton of crude oil imported from exporter $i$ in the spot market under scenario $s \in S_1$
$P_{ij}$	Transportation cost per ton on arc $ij$
$D$	Demand for crude oil
$B_i$	The largest volume of crude oil that can be imported from exporter $i$
$p_{1s}$	Probability of scenario $s \in S_1$ taking place
$\gamma$	Confidence level used in CVaR constraints
$A_{1\gamma}$	The maximum tolerable CVaR value under confidence level $\gamma$ when only considering oil price uncertainty

Decision variables

$q_{1is}^S$	Planned volume of crude oil imported from exporter $i$ in the spot market under scenario $s \in S_1$
$u_{1i}^F$	Planned agreed volume of crude oil in the forward physical contract signed with exporter $i$ when only considering oil price uncertainty
$y_{ijs}$	Actual volume of crude oil transported on arc $ij$ under scenario $s \in S_1$
$\alpha$	Artificial variable for CVaR constraints
$h_{1s}$	Artificial variable for CVaR constraints under scenario $s \in S_1$

Based on the previous analysis, Model 1 is as follows.

##### Model 1

$$\text{Min} \sum_{i \in N_1} P_{1i}^F u_{1i}^F + \sum_{s \in S_1} \sum_{i \in N_1} p_{1s} P_{1is}^S q_{1is}^S + \sum_{s \in S_1} \sum_{i \in N} \sum_{j \in N} p_{1s} P_{ij} y_{ijs} \tag{1}$$

**Subject to**

$$\sum_{\substack{j \in N \\ (i,j) \in A}} y_{ijs} = q_{iis}^S + u_{ii}^F, i \in N_1, s \in S_1 \tag{2}$$

$$\sum_{\substack{j \in N \\ (j,N_2) \in A}} y_{jN_2s} = \sum_{i \in N_1} q_{iis}^S + \sum_{i \in N_1} u_{ii}^F, s \in S_1 \tag{3}$$

$$\sum_{\substack{j \in N \\ (j,i) \in A}} y_{jis} = \sum_{\substack{j \in N \\ (i,j) \in A}} y_{ijs}, i \in N_3, s \in S_1 \tag{4}$$

$$\sum_{i \in N_1} q_{iis}^S + \sum_{i \in N_1} u_{ii}^F \geq D, s \in S_1 \tag{5}$$

$$q_{iis}^S + u_{ii}^F \leq B_i, i \in N_1, s \in S_1 \tag{6}$$

$$y_{ijs} \geq 0, i \in N, j \in N, s \in S_1 \tag{7}$$

$$q_{iis}^S, u_{ii}^F \geq 0, i \in N_1, s \in S_1 \tag{8}$$

CVaR constraints:

$$\alpha + \frac{1}{1-\gamma} \sum_{s \in S_1} p_{1s} h_{1s} \leq A_{1\gamma} \tag{9}$$

$$h_{1s} \geq \sum_{i \in N_1} P_{1i}^F u_{ii}^F + \sum_{i \in N_1} P_{1is}^S q_{iis}^S + \sum_{i \in N} \sum_{j \in N} P_{ij} y_{ijs} - \alpha, s \in S_1 \tag{10}$$

$$h_{1s} \geq 0, s \in S_1 \tag{11}$$

Objective function (1) minimizes the expected total costs for purchasing the planned agreed volume of crude oil in the forward physical contracts, planned volume of crude oil from spot markets, as well as for transporting the crude oil. Constraints (2)–(4) are the flow conservation constraints for  $y_{ijs}$ . Constraint (2) says that for exporters, the volume transported from each exporter is equal to the planned volume imported from its spot market plus the planned volume from its forward physical contract. Constraint (3) says that for the importer, for each scenario, the volumes transported to the importer are equal to the total volumes imported in the spot market plus the total planned volumes from the forward physical contracts signed with exporters. Constraint (4) says that, for other nodes, the volumes transported into those nodes are equal to the volumes transported out of them. Constraint (5) says that the planned agreed volumes in the forward physical contracts plus the volumes imported from the spot market can meet the demand requirement. Constraint (6) says that the planned agreed volume in the forward physical contract signed with exporter  $i$  plus the volume imported in the spot market from exporter  $i$  cannot exceed the largest volume that can be imported from exporter  $i$ . Constraints (7) and (8) define the domains of the decision variables. Constraints (9)–(11) are the CVaR constraints.

For the evaluation of Model 1, we need to find a meaningful definition of what is the planned volume transported on the different links. This will be needed to handle transportation risks. As outlined, we chose to use the expected volume transported on arc  $ij$ , denoted  $x_{ij}$ , and defined as  $x_{ij} = \sum_{s \in S_1} p_{1s} y_{ijs}$ .

Let us then turn to Model 2, which is an evaluation model for Model 1, and the first-stage decisions in Model 2 will be fixed from Model 1. In the second-stage, we will, scenario by scenario, see how the first-stage decisions will work and calculate the real expected total costs of using the results from Model 1.

The notations  $N_1, N_2, N_3, N, A, P_{1i}^F, P_{ij}, D$  and  $B_i$  used in Model 1, are also used in Model 2. In addition, we use:

Sets

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$A_1$	Set of straits and canals
$S_2$	Set of scenarios for crude oil spot price, delivery and transportation ratios

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Parameters

$P_{2is}^S$	Price per ton of crude oil imported from exporter $i$ in the spot market under scenario $s \in S_2$
$P$	Price for unsatisfied demand of crude oil
$w$	Volume of unsatisfied demand of crude oil
$u_{1i}^F$	Planned agreed volume of crude oil in the forward physical contract signed with exporter $i$
$x_{ij}$	Planned volume of crude oil transported on arc $ij$
$Y_{is}$	The delivery ratio of the forward physical contract signed with exporter $i$ under scenario $s \in S_2$
$Z_{ijs}$	Transportation ratio of the planned volume of crude oil transported on arc $ij$ under scenario $s \in S_2$
$\delta_{is}$	Binary values, equal to 1 if $Y_{is}$ is equal to 1, and 0 if $Y_{is}$ is less than 1
$p_{2s}$	Probability of scenario $s \in S_2$ taking place
$M$	A very large number

Decision variables

$q_{2is}^S$	Volume of crude oil imported from exporter $i$ in the spot market under scenario $s \in S_2$
$x_{ijs}$	Actual volume of crude oil transported on arc $ij$ under scenario $s \in S_2$

We will solve Model 2 scenario by scenario. In some scenarios, not all forward crude oil can be delivered due to the events in exporters, or not all volumes can be transported due to the events in straits and canals. And in some scenarios, not even the overall crude oil demand can be satisfied. When solving Model 2, we let the crude oil imported in the forward market be free (it is already paid or promised to be paid in the first stage), and we will therefore take as much as we can.

In each scenario, this is a network flow problem. For each scenario  $s \in S_2$ , if  $Z_{ijs} < 1$ , then

$$x_{ijs} \leq Z_{ijs}x_{ij} \tag{12}$$

That is, if there are events in a strait or canal, the actual volume of crude oil transported does not exceed the planned volume times the transportation ratio, otherwise the actual volume of crude oil transported is unbounded.

For  $i \in N_1$ , if  $Y_{is} < 1$ , then

$$\sum_{\substack{j \in N \\ (i,j) \in A}} x_{ijs} \leq Y_{is} u_{1i}^F \tag{13}$$

$$q_{2is}^S \leq \delta_{is}M \tag{14}$$

That is, for each exporter, if there are events, the volume transported from the exporter is less than or equal to the planned agreed volume in the forward physical contract times the delivery ratio, and the importer cannot purchase crude oil from that exporter in the spot market.

For  $i \in N_1$ , if  $Y_{is} = 1$ , then

$$\sum_{\substack{j \in N \\ (i,j) \in A}} x_{ijs} = q_{2is}^S + u_{1i}^F \tag{15}$$

$$q_{2is}^S + u_{1i}^F \leq B_i \tag{16}$$

That is, for each exporter, if there are no events, the volume transported from the exporter is equal to the volume imported in the spot market plus the planned agreed volume of the forward physical contract. And the volume from the forward physical contract signed with the exporter plus the volume imported in the spot market from the same exporter cannot exceed the largest volume that can be imported.

For  $i \in N_3$ , the flow conservation constraint is satisfied, which is:

$$\sum_{\substack{j \in N \\ (j,i) \in A}} x_{jis} = \sum_{\substack{j \in N \\ (i,j) \in A}} x_{ijs} \tag{17}$$

If the total volume of crude oil transported to the importer from all the exporters in the forward and spot market cannot satisfy the demand due to the events, the volume of unsatisfied demand of crude oil will be imported from other places with a higher price (or this can be seen as the cost of lack of supply).

When we calculate the total costs of each scenario, if the forward crude oil cannot be totally delivered due to the events in exporters, we only pay for the crude oil that can be delivered. If some forward crude oil cannot be transported due to the events in straits and canals, we only pay for the crude oil that can be transported. This is because either we do not pay for it because we cannot get it, or we pay for it but we can get the money back maybe by selling it later. In any case, we do not pay for it in this period. In addition to the costs in the forward market, the costs in the spot market and the transportation costs, for a scenario in which demand is not satisfied, there is another cost called penalty, which is expressed by a high price times the volume of unsatisfied demand. It is expressed as  $wP$ . Then the expected total cost of Model 2 equals the sum of the total cost in each scenario multiplied by the probability

of each scenario, which is the real cost for Model 1.

The parameter  $x_{ij}$  used in Model 2 is a decision variable in Model 3, and parameters  $u_{1i}^F$ ,  $P$ , and  $w$  used in Model 2 are not used in Model 3. Other notation used in Model 2 is all used in Model 3. And the parameter  $\gamma$ , and the decision variable  $\alpha$  used in Model 1 are also used in Model 3. The other special notations used in Model 3 are as follows:

Parameters

$A_{2\gamma}$	The maximum tolerable CVaR value under confidence level $\gamma$ when considering physical risks
$\varepsilon$	A very small number

Decision variables

$m_{1i}^F$	Planned agreed volume of crude oil in the forward physical contract signed with exporter $i$ when considering physical risks
$x_{ij}$	Planned volume of crude oil transported on arc $ij$
$h_{2s}$	Artificial variable for CVaR constraints under scenario $s \in S_2$

The two-stage stochastic programming for Model 3 is established as follows.

**Model 3**

$$\min \sum_{s \in S_2} \sum_{i \in N_1} p_{2s} P_{1i}^F Y_{is} m_{1i}^F + \sum_{s \in S_2} \sum_{i \in N_1} p_{2s} P_{2is}^S q_{2is}^S + \sum_{s \in S_2} \sum_{i \in N} \sum_{j \in N} p_{2s} P_{ij} x_{ijs} \tag{18}$$

Subject to

$$\sum_{\substack{j \in N \\ (i,j) \in A}} x_{ijs} = q_{2is}^S + Y_{is} m_{1i}^F, i \in N_1, s \in S_2 \tag{19}$$

$$\sum_{\substack{j \in N \\ (j,N_2) \in A}} x_{jN_2s} = \sum_{i \in N_1} q_{2is}^S + \sum_{i \in N_1} Y_{is} m_{1i}^F, s \in S_2 \tag{20}$$

$$\sum_{\substack{j \in N \\ (j,i) \in A}} x_{jis} = \sum_{\substack{j \in N \\ (i,j) \in A}} x_{ijs}, i \in N_3, s \in S_2 \tag{21}$$

$$m_{1i}^F \leq \sum_{\substack{j \in N \\ (i,j) \in A}} x_{ij} \leq B_i, i \in N_1 \tag{22}$$

$$\sum_{\substack{j \in N \\ (j,N_2) \in A}} x_{jN_2} = D \tag{23}$$

$$\sum_{\substack{j \in N \\ (j,i) \in A}} x_{ji} = \sum_{\substack{j \in N \\ (i,j) \in A}} x_{ij}, i \in N_3 \tag{24}$$

$$\sum_{i \in N_1} q_{2is}^S + \sum_{i \in N_1} Y_{is} m_{1i}^F \geq D, s \in S_2 \tag{25}$$

$$q_{2is}^S + Y_{is} m_{1i}^F \leq B_i, i \in N_1, s \in S_2 \tag{26}$$

$$q_{2is}^S \leq \delta_{is} M, i \in N_1, s \in S_2 \tag{27}$$

$$x_{ijs} \leq Z_{ijs} x_{ij} + [Z_{ijs} - 1 + \varepsilon]^+ M, (i, j) \in A_1, s \in S_2 \tag{28}$$

$$x_{ijs} \geq 0, x_{ij} \geq 0, i \in N, j \in N, s \in S_2 \tag{29}$$

$$q_{2is}^S, m_{1i}^F \geq 0, i \in N_1, s \in S_2 \tag{30}$$

CVaR constraints:

$$\alpha + \frac{1}{1 - \gamma} \sum_{s \in S_2} p_{2s} h_{2s} \leq A_{2\gamma} \tag{31}$$

$$h_{2s} \geq \sum_{i \in N_1} P_{1i}^F m_{1i}^F Y_{is} + \sum_{i \in N_1} P_{2is}^S q_{2is}^S + \sum_{i \in N} \sum_{j \in N} P_{ij} x_{ijs} - \alpha, s \in S_2 \tag{32}$$

$$h_{2s} \geq 0, s \in S_2 \tag{33}$$

The objective function (18) represents the expected total costs of importing and transporting crude oil from exporters to the importer, considering not only the oil price uncertainty but also the physical risks. The term  $\sum_{s \in S_2} \sum_{i \in N_1} p_{2s} P_{1i}^F Y_{is} m_{1i}^F$  in (18) represents the expected cost for the delivered volume of crude oil in the forward physical contracts, while  $\sum_{s \in S_2} \sum_{i \in N_1} p_{2s} P_{2is}^S q_{2is}^S$  represents the expected cost for crude oil imported in the spot market. The sum  $\sum_{s \in S_2} \sum_{i \in N} \sum_{j \in N} p_{2s} P_{ij} x_{ijs}$  in (18) represents the expected cost for transporting crude oil from exporters to the importer. Constraints (19)–(21) are the flow conservation constraints. Constraint (19) says that the volume transported from each exporter is equal to the volume imported from the spot market plus the delivered volume of the planned forward physical contract. Constraint (20) says that the volumes transported to the importer are equal to the total volumes imported in the spot markets plus the total delivered volumes from the forward physical contracts. Constraint (21) says that for other nodes, the volumes transported to those nodes are equal to the volumes transported from them. As for constraint (22), it says that the planned volume transported from exporter  $i$  is greater than or equal to the agreed volume in the forward physical contract signed with exporter  $i$ , and is less than or equal to the largest volume that can be imported from exporter  $i$ . Constraint (23) says that the total planned volumes transported to the importer are equal to the demand. Constraint (24) is also a flow conservation constraint for the planned transportation volume. Constraint (25) says that the crude oil demand is respected. Constraint (26) says that the delivered volume from the forward physical contract signed with exporter  $i$  plus the volume imported in the spot market from exporter  $i$  cannot exceed the largest volume that can be imported from exporter  $i$ . Constraint (27) says that if exporter  $i$  cannot deliver the agreed volume of crude oil in the forward physical contract, then the importer cannot purchase crude oil from exporter  $i$  in the spot market. In constraint (28),  $X^+$  takes value  $X$  if  $X \geq 0$ , 0 otherwise. So constraint (28) represents that if a certain strait or canal is affected by extreme events, the actual volume of crude oil transported through it does not exceed the planned volume that it transports times the transportation ratio. If straits or canals are not affected by extreme events, the actual volumes of crude oil transported through them are unbounded. Constraints (29) and (30) define the domains of the decision variables. Constraints (31)–(33) are the CVaR constraints for restricting the expected total costs in the worst case scenarios to be within an acceptable level.

## 5. Numerical test

### 5.1. Basic information of the numerical test

We use China as the importer in our numerical test. We have chosen to use a concrete case like this, even if we lack some data, as we feel it is easier to grasp the qualitative results with a quasi-real case. But this must not be read as a decision model for China. In 2017, China imported 419 million tons of crude oil, the top ten crude oil exporters for China are Russia, Saudi Arabia, Angola, Iraq, Iran, Oman, Brazil, Venezuela, Kuwait and the United Arab Emirates (UAE) (International Trade Center, 2018). Most crude oil to China originates in the Middle East, followed by Africa and Latin America. This paper selects Saudi Arabia, Oman, Iraq, Iran, UAE and Kuwait in the Middle East, Angola, Congo, South Sudan and Libya in Africa, and Venezuela, Colombia and Brazil in Latin America as the crude oil exporters for the test. The volumes imported from these exporters add up to 71.5% of China’s total imported crude oil in 2017 (International Trade Center, 2018). Fig. 2 is the maritime transportation network for China’s imported crude oil from these exporters. The straits and canals in the maritime transportation network include the Strait of Hormuz, the Strait of Malacca, the



Fig. 2. Transportation network for China’s imported crude oil.



Sunda Strait, the Lombok Strait, the Strait of Gibraltar, the Taiwan Strait, the Bab el Mandeb, the Suez Canal and the Panama Canal. The planning period in this paper is three months, so the demand of imported crude oil for the planning period is 75 million tons, which is 71.5% of a quarter of the total imported volume in 2017.

As mentioned earlier, in our problem there are correlations between political risks of different exporters, crude oil prices, and risks of straits or canals. We need to make some assumptions about these correlations. Though based on literature, these assumptions are of course to some extent subjective. But we believe them to be good enough for the purpose of this paper, namely to shed light on the importance of physical risks.

There are high correlations between political risks of exporters in the Middle East. For example, the relationship between Saudi Arabia and Iran has always suffered from tension and conflict, and religion is the conflict escalator (Alghunaim, 2014). Saudi Arabia is the representative of Sunni, and Iran is the representative of Shiite. Most countries in the Middle East are governed by Sunnis, but Iran, Iraq and Syria are governed by Shiite. Saudi Arabia and Iran have formed two camps in the Middle East, if one is involved in a conflict, the other is probably involved in the conflict as well. So there are large positive correlations between political risks of Saudi Arabia and Iran. Iraq, after Saddam Hussain with the majority of Shiites in the Iraqi government, became a new Iranian ally (Alghunaim, 2014), so there are large positive correlations between political risks of Iraq and Iran. Kuwait and UAE have good relationships with Saudi Arabia, so there are relatively small positive correlations between political risks of those three countries (Tao, 2017). Oman is a neutral country and has good relationships both with Saudi Arabia and Iran. So there are relatively small positive correlations between political risks of Oman and other countries (Zhang and Su, 2017). The causes for political risks of Angola, Congo, South Sudan and Libya in Africa are mainly civil conflicts or military interventions from Western countries, so their political risks are relatively independent. For reasons of historic, geographic, and cultural nature, and due to an intense and complex relationship, there are positive correlations between political risks of Venezuela and Colombia. In 2016, Venezuela announced a “freeze” in relations with Brazil, and relations between Venezuela and Brazil broke down. There are no big conflicts between Venezuela and Brazil, so there is a relatively small correlation between political risks of those countries. Exporters in one region such as the Middle East, Africa or Latin America are relatively far from exporters in other regions, this paper assumes that political risks of exporters in different regions are independent.

There are positive correlations between political risks of exporters and crude oil prices. In the case of political unrest of exporters, we will normally see disruptions of supply of crude oil, and the supply and demand in the international crude oil market will be out of balance. As a result, the global crude oil prices will fluctuate. As the global crude oil market is highly integrated, the crude oil prices of other exporters will also be affected, leading to large positive correlations between crude oil prices of exporters. As for the correlations between political risks and straits or canals risks, they are also positive whenever the two are geographically close. For example, if Iran is involved in a conflict, the Strait of Hormuz is probably also affected.

According to Cheng and Duran (2004), a typical total unitary crude transportation cost is in the range of US\$ 1.50–3.00 per barrel of crude. We assume that the transportation cost from Iran to China is US\$ 1.50 per barrel of crude. According to the transportation distance of each arc in the maritime transportation network for China’s imported crude oil and the conversion relationship between ton and barrel of crude oil, the transportation cost per ton on each arc can be calculated.

The largest volume of crude oil that can be imported from each exporter is affected by many factors, and we do not have real data. Because the crude oil production in Congo and South Sudan is relatively small, we set the largest volume of crude oil that can be imported from Congo and South Sudan to 5,000,000 tons. For the other exporters, the largest volume is 12,000,000 tons.

Again, these are assumptions, and certainly not provably right. But we believe them to be good enough for our goal: to understand qualitatively the role of physical risks.

## 5.2. Scenario generation

The stochastic phenomena in our problem are, as mentioned above, spot crude oil prices of exporters and physical risks. Since the Brent price is a benchmark price, and crude oil prices of exporters on the spot market are determined by referring to the Brent price, we only generate scenarios for the Brent price. When generating the scenarios for the Brent price, we use the latest observed Brent price as the base price, and generate positive or negative price increments to be added to the base price (Gu et al., 2018). We do this since the Brent price can be considered as a Lévy process (Krichene, 2008; Gencer and Unal, 2012) which has independent increments. The base price is the monthly average Brent price in December 2018, which is about 422 USD/ton. And the average monthly Brent prices from May 1987 to December 2018, provided by the U.S. Energy Information Administration (EIA), are used to obtain the distribution for the Brent price increments. According to the historical monthly Brent price increments, its marginal distribution is reasonably triangular and symmetric. The marginal distribution is controlled by the lower limit, mode and upper limit which are  $(-190, 0, 190)$ . Since the expected value of the price increments equals 0, the expected value of the Brent price on the spot market is assumed to be equal to the latest observed Brent price. After the Brent price is generated, the prices of exporters are then adjusted proportionally based on the relationship between the prices of exporters and the Brent price in December 2018.

In terms of the delivery and transportation ratios, we do not have real data, so we use reasonable guesses. We use discrete marginal distributions to describe them. Because conflict is a small probability event, the probability of value 1 for the delivery ratios is set very high. Our logic for setting the marginal distributions is as follows. For Saudi Arabia, Iran and Iraq, once there is a conflict in these three countries, they are likely to be the direct participants of the conflict, and crude oil production will be seriously affected. So we assume there are no possible values strictly between 0.5 and 1 for the delivery ratios for these three countries, the values are all between 0.1 and 0.5 (or 1), and the probability will gradually decrease when ratios increase from 0.1 to 0.5. As for Oman, UAE and Kuwait, as they are likely to be involved in the conflict, but not direct participants, crude oil production is relatively less affected. So

we assume that the values for the delivery ratios for these three countries are between 0.6 and 0.9 (or 1). And since the crude oil production will be affected to some extent but not very seriously, the probability of low and high values for the delivery ratios is relatively small. So we assume that the probability will first increase and then decrease when ratios increase from 0.6 to 0.9. The political risks of the four African countries are mainly caused by their own civil conflicts. Hence, they and the three countries in Latin America have the same logic as Saudi Arabia, Iran and Iraq for setting marginal distributions. The risk level of different exporters can be compared according to the probability of different values of the delivery ratio. For example, the political risk of Iran is relatively higher than that of Saudi Arabia, so the probability of low values of the delivery ratio for Iran is higher than that for Saudi Arabia.

As for the marginal distributions for the transportation ratios, the probability of value 1 should also be the highest. When there are events in straits and canals, in most cases, although the total volume of crude oil cannot be transported, most of it can. For example, if, originally, there are ten vessels planning to transport through a strait, when there are difficulties in that strait, in most cases, nine or eight vessels can go through it, in rare cases, no vessel or only one vessel can go through it. So we assume the values of transportation ratios are between 0.5 and 1, and the probability will show an increasing trend when values increase from 0.5 to 1. Similarly, the higher the risk, the higher the probability of low values of the transportation ratio.

The marginal distributions of delivery ratios for the 13 exporters and transportation ratios for the 9 straits and canals are shown in Tables A.1 and A.2, which are listed in Appendix A. We also do not have real data of correlations between the Brent price, delivery ratios and transportation ratios. We set up a reasonable correlation matrix of the 23 stochastic variables, as shown in Table A.3, which is also listed in Appendix A.

We use the marginal distribution of monthly Brent price increments to generate scenarios for the Brent price, which is called  $S_1$  and is used in Model 1. And we use the marginal distributions of the monthly Brent price increments, delivery and transportation ratios, as well as the correlation matrix and the version of the scenario-generating heuristic proposed by Kaut (2014) to generate scenarios for the 23 stochastic variables, which is called  $S_2$  and is used in Models 2 and 3. We generate 10 scenario trees, each consisting of 100 scenarios for the two scenario sets. We set the probability of each scenario in the two sets to 0.01.

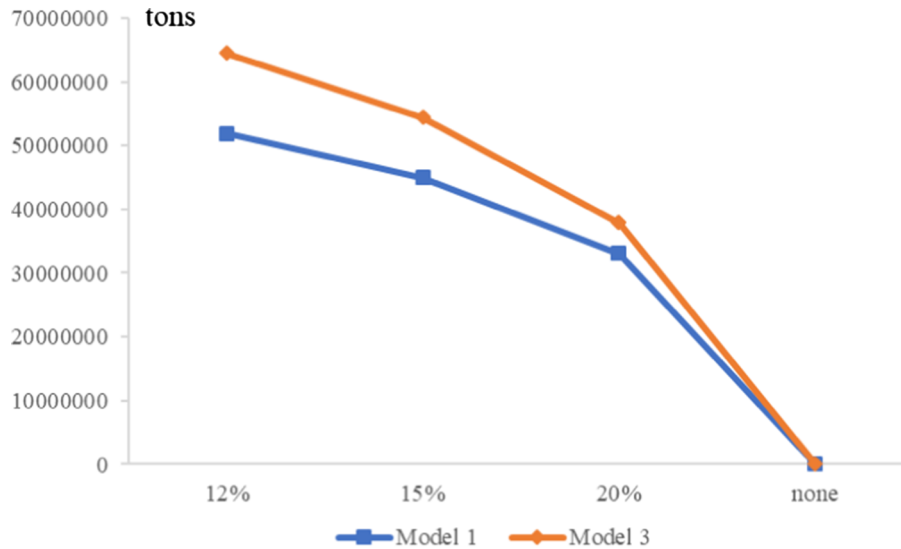
Notice that we have two sets of scenarios,  $S_1$  and  $S_2$ . We could manage with only one, namely  $S_2$ , but have chosen two for the following reason. When establishing the scenarios, we need to determine how many scenarios we need. And since the complexity of solving a model grows seriously with the number of scenarios, a low number is important. Scenario set  $S_2$  covers more random variables than  $S_1$ , and the random variables in  $S_1$  are contained in those in  $S_2$ . So we could reasonably need fewer scenarios in  $S_1$  than in  $S_2$ . But with 100 scenarios all the models are solved very easily, and the in-sample stability tests (Kaut and Wallace, 2007) for all the models confirm an in-sample stability, in which the gap among the objective values between different scenario trees is less than 0.4%. So we keep 100 scenarios also for  $S_1$  and do not try to reduce it. This way we know that the noise coming from the scenario generation is very small, less than one half of one percent.

The forward price of each exporter is set 1% above the expected value of the stochastic spot price, which is the latest observed price. We employ the monthly average import price from each exporter in December 2018 as the latest observed price. The forward price of each exporter, and the relationship between the prices of exporters and the Brent price in December 2018 are shown in Table 1. We apply the same level of risk aversion in all the models to make the results comparable. We first solve the problem without the CVaR constraints (risk neutral) and set the CVaR value to be a certain percentage higher than the objective value without the CVaR constraints. The larger the CVaR value, the less risk averse is the importer. The confidence level is set to be 95%. The price for unsatisfied demand is set five times the forward price of Oman, whose price is the highest among the thirteen exporters. This is simply a way to make sure that the model will always deliver oil when at all feasible, and not an estimate of the cost of unsatisfied demand.

**Table 1**  
The forward prices and relationship between the prices of exporters and the Brent price in December 2018.

Exporter	Forward price	Relationship
Saudi Arabia	500.6906	1.1758
Iran	500.6943	1.1759
Iraq	494.7674	1.1619
UAE	520.7070	1.2229
Kuwait	495.9249	1.1647
Oman	528.8427	1.2420
Angola	492.9363	1.1576
Congo	496.8011	1.1667
South Sudan	425.1211	0.9984
Libya	508.0018	1.1930
Venezuela	423.3417	0.9942
Colombia	449.5343	1.0557
Brazil	469.0157	1.1015

Note: The unit of the forward prices is USD/ton, and the relationship represents the value of the exporter's price divided by the Brent price in December 2018.



**Fig. 3.** Total planned volume of crude oil imported in the forward market of Models 1 and 3 with the increase of the CvaR value. Note: None represents that there are no CVaR constraints.

### 5.3. Results analysis

An overview of the numerical results can be found in this section. More details are presented in Appendix B.

#### 5.3.1. Decisions in the forward market

Fig. 3 shows the total planned volume of crude oil imported in the forward market with changes of the importer's risk attitude, when considering and not considering physical risks. We can observe that the total planned volumes of crude oil bought in the forward market decrease regardless of whether or not the physical risks are considered when the importer becomes less risk averse. This is expected because the forward market is a risk reducing instrument. And it is not surprising to observe that except when the importer is risk neutral, the planned volume of forward crude oil imported is always larger when physical risks are taken into account, compared to that when physical risks are not considered. When the importer is risk neutral, no forward crude oil will be imported regardless of physical risks.

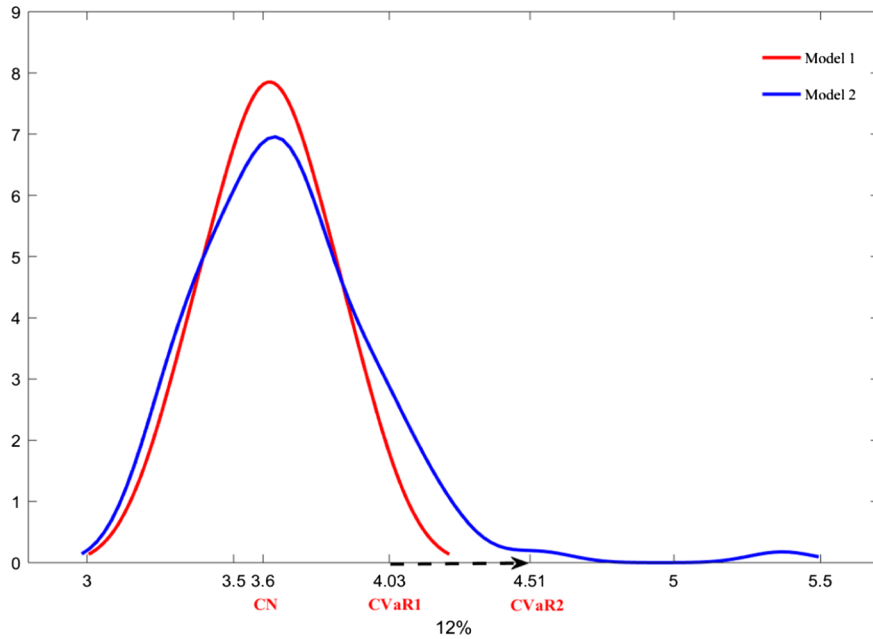
When only oil price uncertainty is taken into consideration, the importer buys less crude oil in the forward market as shown above, and they think they have controlled the financial risks. The importer ignores the physical risks, but they are really there, so the financial risks are much higher than the importer thinks. We compare the CVaR values of Models 1 and 2 to see how risky is the decisions of only considering oil price uncertainty, as shown in Table 2. CVaR1 in Table 2 refers to the CVaR values of Model 1 under different risk attitudes of the importer. CVaR2 refers to the expected total costs in the worst 5% scenarios of Model 2, which is the real risk of using Model 1. As shown in Table 2, the real risks are about 11% higher than the importer thinks.

We use Fig. 4 for illustration. CN in Fig. 4 refers to the expected total cost without the CVaR constraints (risk neutral), and CVaR1 is the CVaR value of Model 1, which is 12% higher than CN. Finally, CVaR2 is the real risk of using Model 1. As can be seen in Fig. 4, if the importer only considers oil price uncertainty and ignores the physical risks, the cost distribution (of Model 2) is flatter and the tail becomes longer. CVaR2 moves to the right, so the real risk is much higher, in fact, 11.9% higher than what the importer thinks.

The extreme tail of the cost distribution of Model 2 is caused by the penalty, and the unit penalty cost is set very high to make sure that we always import oil if we can. It is difficult to say what the real unit penalty should be. It might represent a genuine lack of oil supply, but more likely represents a much more expensive way to obtain oil. To illustrate that the qualitative observations in Fig. 4 remain true irrespective of the unit penalty cost, we calculated the marginal cost of importing and transporting oil in the most extreme scenario, and used this marginal cost to replace the unit penalty. This is most likely a conservative measure of the cost (as additional oil would cost more than that). Then the CVaR2 shifts to the left, and is reduced to 4.27. So the extreme right tail disappears, but the general picture remains.

**Table 2**  
CVaR value of Models 1 and 2 (Unit: 10 billion USD).

Risk attitude	12%	15%	20%
CVaR1	4.03	4.14	4.32
CVaR2	4.51	4.60	4.78
Difference	11.9%	11.1%	10.6%



**Fig. 4.** Cost distribution of Models 1 and 2 when the CVaR value of Model 1 is 12% higher than the objective value without the CVaR constraints (Unit: 10 billion USD).

We further analyze the differences in the composition of imported crude oil in the forward market. If only oil price uncertainty is taken into account, crude oil will be imported by comparing the oil prices and transportation costs of the exporters. Exporters having low oil price and being close to the importer will be preferred. However, if the importer is rather risk averse, and takes the physical risks into consideration, exporters will be more diversified to handle the physical risks. Less crude oil will be imported from the larger regions that only have one strait or canal to transport the crude oil (and whose transportation risks are also relatively high), although those regions are closer to the importer. In addition, for the regions with zero correlations among the exporters, relatively larger volume of crude oil will be imported from exporters that have relatively low political risk and low oil price. Less crude oil will be imported from exporters that have relatively high political risk, or from exporters that not only have relatively high political risk, but also need to transport through straits or canals with high transportation risks. In terms of regions with correlations among the exporters and which use the same straits or canals, crude oil will be imported from the exporter that has relatively low political risk and oil price, as well as small correlations among itself and other exporters. Moreover, when there are two large exporters that have relatively high correlations among themselves and other exporters in one region and use the same straits or canals, crude oil will be imported from the exporter having an overall advantage of both oil price and political risk. But the volume imported from the exporter will be relatively small.

When the importer is less risk averse, while taking physical risks into consideration, volumes from exporters that have relatively high political risks, oil prices and transportation costs will be reduced. And volumes from exporters that have relatively high political risks and oil prices, as well as need to transport through straits or canals with high transportation risks will be reduced as well. As the importer becomes even less risk averse, volume from the above exporters will continue to decrease. Besides, volume from exporters that have relatively low political risk but overall high expense on oil price and transportation cost will begin to decrease. By contrast, volume from exporters that have high political risk but very low oil price will increase when the importer become less and less risk averse.

The advantages of taking physical risks into account are that the forward crude oil can be used more effectively and less crude oil needs to be imported in the spot market. This can avoid high cost volatility and unsatisfied demand for the importer, compared to that when only oil price uncertainty is taken into consideration.

### 5.3.2. Decisions of the planned volume transported through straits and canals

If the importer only considers oil price uncertainty, only transportation costs need to be compared to make transportation decisions. We will next discuss decisions when physical risks are taken into account. The straits or canals that have relatively low transportation costs, but high risks, are first analyzed.

If those straits and canals are very important, and have no substitutable straits and canals (e.g., the Strait of Hormuz in our numerical test), while the importer is rather risk averse, smaller volume of crude oil will be planned to transport through them, compared to the case when only oil price uncertainty is taken into account, as shown in Fig. 5. However, if the importer is less risk averse, the volumes will increase due to their low transportation costs. Another reason for the increase is that since the planned volumes increase, if there are events, the actual volumes that can be transported through them also increase. Less crude oil needs to



Fig. 5. The planned volume transported through straits and canals of Models 1 and 3 with the increase of the CVaR value.

be imported from exporters in other regions in the spot market, where there may be no spot crude oil available or the crude oil cannot be transported due to the events. If those straits and canals have substitutable straits or canals in the same region, and the substitutable straits or canals have higher transportation costs but lower risks (e.g., the Strait of Malacca, the Bab el Mandeb and the Suez Canal in our numerical test), the planned volume transported through them will always be larger regardless of the risk attitude of the importer. It is because if there are events in them, less crude oil needs to be transferred to their substitutable straits or canals, and the transportation cost will not increase much.

We will further discuss the planned volume for the straits or canals that have relatively low transportation risks, but high costs. If those straits and canals have substitutable straits or canals in the same region, and the substitutable straits or canals have lower transportation costs (e.g., the Sunda Strait, the Lombok Strait and the Strait of Gibraltar in our numerical test), the planned volume transported through them will be zero. The planned volume transported through them is also zero when only oil price uncertainty is taken into account. If those straits and canals have substitutable straits or canals in another region, and transferring crude oil to the substitutable straits or canals will increase transportation costs (e.g., the Panama Canal in our numerical test), the planned volume transported through them will always be smaller.

Taking physical risks into account can avoid more crude oil detours to substitute straits or canals, which can save transportation costs. The chance of observing unsatisfied demand is also reduced.

5.3.3. Expected total cost and cost variability

When physical risks are taken into account, the expected total cost will decrease if the importer becomes less risk averse. This is expected because a smaller volume of forward crude oil will be imported. When only oil price uncertainty is considered, as a whole,

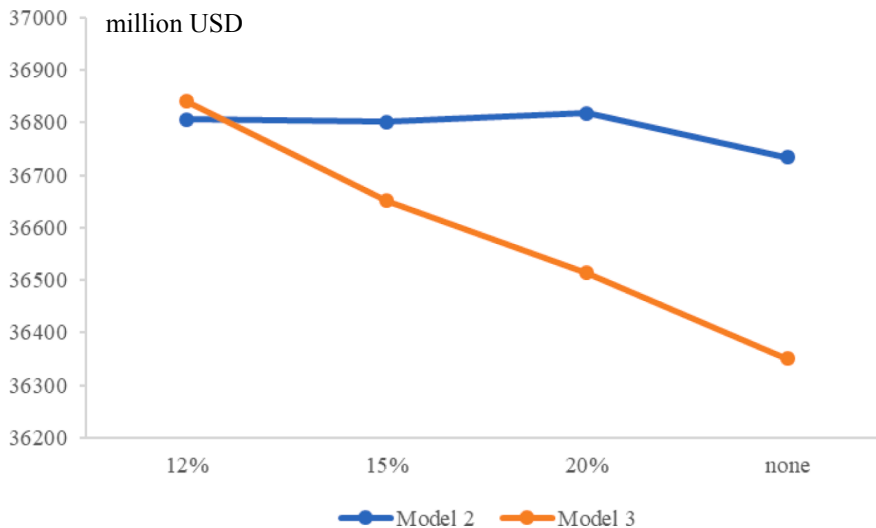


Fig. 6. The expected total cost of Models 2 and 3 with the increase of CVaR value.

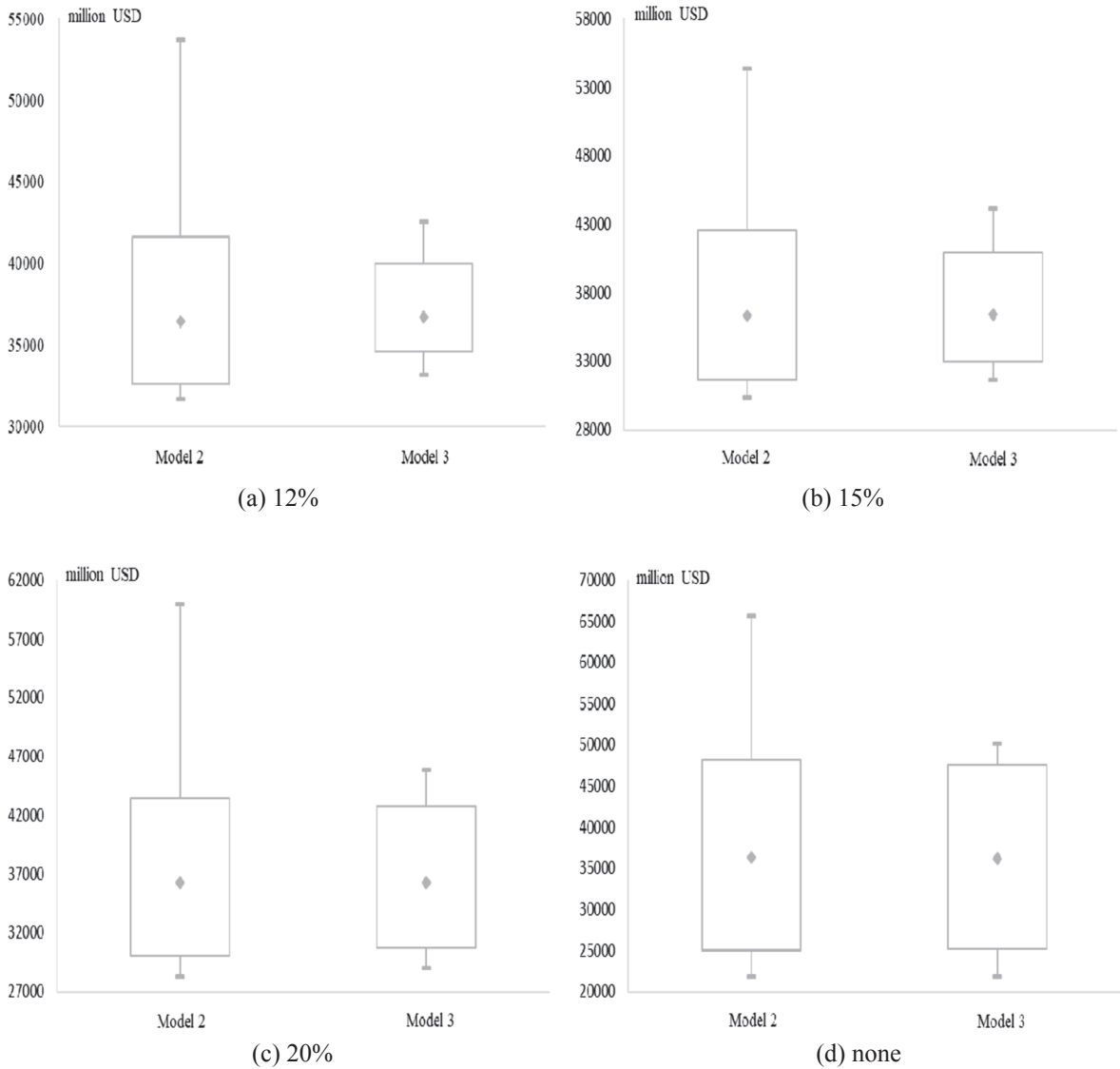


Fig. 7. Box plot for cost comparisons between Models 2 and 3 for different CVaR.

the *true* expected total cost (as measured by Model 2) first increases and then decreases if the importer becomes less risk averse (of course, the total costs within Model 1 will behave as in Model 3; a steady decrease as risk aversion decreases). The reason is that if the importer is rather risk averse, the decrease of the expected cost in the forward market is smaller than the increase of the expected penalty when the importer's risk aversion decreases. As the importer becomes less and less risk averse, the decrease of the expected cost in the forward market is larger than the increase of the expected penalty, so the expected total cost will then decrease. In addition, the expected total cost is first lower and then higher than when physical risks are considered, as shown in Fig. 6. This is because when the importer is rather risk averse and only oil price uncertainty is considered, the expected cost in the forward market is much lower compared to the case when physical risks are taken into account. And since the expected penalty is not too high, the expected total cost is lower when only oil price uncertainty is considered. However, when the importer becomes less risk averse, the expected cost in the forward market is still lower when only oil price uncertainty is considered, but the difference is smaller. And the volume of unsatisfied demand increases, so does the expected penalty, so the expected total cost is higher when only oil price uncertainty is considered.

We also use a box plot to show how the total cost vary for all 100 scenarios with changes of the importer's risk attitude, when considering and not considering physical risks, as reported in Fig. 7. The whisker on either side of the box represents the 5% scenarios with the highest (upside whisker) or the lowest (downside whisker) total costs, and the box represents the remaining 90%.

There are severe cost consequences in some scenarios when only oil price uncertainty is taken into consideration. If only oil price uncertainty is considered, when the physical risks are realized, in some scenarios, some forward crude oil cannot be delivered or transported, more crude oil needs to be imported in the spot market. And there is also unsatisfied demand in some scenarios.

Therefore, there will be higher risks in the extreme cases than that when physical risks are considered. And the most severe costs consequences will be higher when the importer becomes less risk averse due to less forward crude oil imported.

In addition, it can also be seen from Fig. 7 that the total costs become more volatile if the importer becomes less risk averse regardless of whether the physical risks are considered or not. This is because when the importer is less risk averse, less forward, but more spot crude oil will be imported. And the total cost is always more volatile when only oil price is considered, compared to the case when physical risks are taken into account, due to the more spot crude oil imported and unsatisfied demand. However, when the importer becomes less risk averse, more crude oil will be imported in the spot market regardless of whether the physical risks are considered or not, so the difference of cost variability will be smaller. As discussed above regarding Fig. 4, the penalty will also cause the cost in the worst scenario of Model 2 to be very high as shown in Fig. 7, but it will not affect the qualitative observations in Fig. 7.

In conclusion, we see that if the importer is rather risk averse, the expected total cost is lower when only oil price uncertainty is considered. But the importer will experience higher cost volatility and financial risks in the extreme cases. Since the importer is rather risk averse, they cannot bear the higher cost volatility and financial risks in the extreme cases. Therefore, it is necessary for the importer to consider physical risks to do crude oil import and transportation planning. If the importer is less risk averse, there are higher expected total cost, cost volatility and financial risks in the extreme cases when only oil price uncertainty is taken into account, so it is also necessary for the importer to consider physical risks.

## 6. Conclusion

Crude oil price uncertainty is most commonly considered when decision makers control the financial risks of imported crude oil. This paper investigates whether physical risks, such as the exporters' political risks, as well as transportation risks, should be taken into account when controlling financial risks at a tactical level. To model the problem, three two-stage stochastic programming models are proposed. Through a numerical test we study the effects of physical risks on the decisions and costs in line with the importer's risk attitude. It is found that unless the importer is risk neutral, more forward crude oil will be imported and exporters will be more diversified when physical risks are considered, compared to only oil price uncertainty. When the importer is risk neutral, there is never any forward crude oil imported regardless of physical risks. In addition, for straits and canals that have low transportation costs but high risks, if they are very important and have no substitutable straits or canals, as well as the importer is rather risk averse, the planned volume transported through them will be smaller when physical risks are considered. However, if the importer is less risk averse, the volume will be larger due to their low transportation costs. Another reason for the larger volume is that if there are events, the actual volumes that can be transported through them will also be larger, and less crude oil needs to be imported from exporters in other regions in the spot market, where there may be no spot crude oil available or the crude oil cannot be transported due to the events. This can prevent unsatisfied demand. If those straits and canals have substitutable straits or canals with higher transportation costs but lower risks, the volume will be larger when physical risks are taken into account. This is because if there are events in them, less crude oil needs to be transferred to their substitutable straits or canals, and the transportation cost will not increase much. Moreover, there will be higher financial risks in the extreme cases and higher cost volatility of the total cost when only oil price uncertainty is considered, compared to the case when physical risks are taken into consideration. So it is necessary for the importer to consider physical risks to control the financial risks when doing crude oil import and transportation planning at a tactical level.

To sum up, the major managerial insights are:

- If physical risks are not considered, the real financial risks will be substantially larger than what might seem the case from an analysis based on just oil price uncertainty.
- When physical risks are taken into account, the geographical distribution of forward oil purchases is strongly affected by the correlations among risks. Positively correlated risks will, as always, increase the overall risks, and should therefore be limited. Hence, forward purchases are guided by more than oil prices and transportation costs – which will always be part of the overall picture.
- If physical risks are included, the amount of oil bought in the forward market will increase in order to secure against the very same risks. As a result of forward prices exceeding expected spot prices, and the spread of purchases described in the previous item, the overall costs will then increase. However, as a result, the financial risks are reduced, by removing the most severe cases from the “only crude oil price” setup.

This paper has some limitations that could be addressed in future research. First, the planned volume of transported crude oil through straits and canals is used as the base for calculating reductions, when there are events in certain straits or canals. Other ways for capacity reduction calculations of straits and canals would be an interesting subject in the future study. Second, the capacities of straits and canals that are not affected by extreme events are assumed unbounded. Determining appropriate bounds for them would be a possible future extension.

## CRedit authorship contribution statement

**Shuang Wang:** Conceptualization, Software, Formal analysis, Writing - original draft, Investigation. **Stein W. Wallace:** Methodology, Writing - review & editing, Supervision. **Jing Lu:** Data curation. **Yewen Gu:** Methodology, Software.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.tre.2019.101824>.

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